泥砂沉降時間-空間動態變化：分析不同孔口高度對排砂效率之影響

Temporal and Spatial Dynamics of Sediment Settling: Analyzing the Impact of Varying Orifice Heights on Sediment Release Efficiency

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摘　要

水庫淤積是全球性的水資源問題。有效的排砂操作是延續水庫壽命的關鍵，比新建水庫更具經濟與環境效益的永續策略。本研究透過模型試驗，探討影響排砂效率的兩個關鍵因子：排砂孔口高度與初始泥砂濃度。研究方法採用一座具備五個不同高度排砂孔的柱狀試驗桶來模擬水庫的垂直剖面，並在40,000至60,000 ppm的初始濃度下進行試驗。研究成果顯示，在排砂過程中不同孔口高度的排砂濃度會維持一段時間的穩定，隨後在某一特定時間點產生驟降，此現象的物理意義為清渾交界面低於排砂孔口的高度。此外，排砂效率與孔口高度有顯著的線性關係。孔口位置越低，排砂效率越高，底層孔口之排砂效率明顯遠高於近表層孔口。本研究最重要的貢獻在於應用量測所得的時間序列濃度變化數據定義出無因次濃度與時間項，分析顯示不同孔口高度與初始濃度在無因次化的座標系統中能夠回歸出一條通用排砂曲線，可用來預測開啟不同孔口排砂所需時間。未來若可應用在真實場域，可進一步優化颱風時期之排砂效率，在耗用最少水資源的前提下達到最大的防淤效益。

關鍵字: 水庫淤積、排砂效率、無因次分析、孔口高度、通用排砂曲線

Abstract

Reservoir sedimentation is a significant issue affecting global water resources. Effective desilting is a sustainable strategy to extend reservoir lifespan and is more economical and eco-friendly than building new dams. This study uses an experimental model to investigate two key factors in desilting efficiency: orifice height and initial sediment concentration. The method involved a cylindrical experimental barrel with five orifices at different heights to simulate a vertical profile of the reservoir. Experiments were conducted with initial concentrations ranging from 40,000 to 60,000 ppm. The results confirm a strong correlation between desilting efficiency and orifice height. Efficiency increases almost linearly as the orifice is lowered. This is because a sharp drop in concentration occurs when the interface between turbid and clear water falls below the orifice level. Lower orifices delay this point, allowing for a longer period of high-concentration discharge, which explains their higher efficiency. A major contribution of this research is consolidating the experimental data into a single universal releasing curve using dimensionless analysis. This predictive curve can estimate the time required for desilting at different orifices, providing a scientific basis for optimizing reservoir operations. This helps achieve maximum sediment release with minimal water use, supporting sustainable reservoir management.

Keywords: reservoir deposition, desilting efficiency, non-dimensional analysis, orifice height, universal releasing curve

Chapter 1 Introduction

1.1 Motivation

Although existing research has extensively explored reservoir sedimentation mechanisms and various sediment discharge methods, there remains a significant research gap regarding how the height of sediment discharge Orifices precisely affects discharge efficiency under extreme rainfall conditions with drastic changes in sediment concentration entering the reservoir. Additionally, there is a lack of experimentally established, universal, and predictive sediment discharge models. This study aims to fill the gap concerning the relationship between the Orifice elevation and sediment discharge efficiency by conducting systematic experimental tests using a small-scale laboratory model simulating a reservoir. Experiments were performed with different sediment discharge Orifice heights and varying initial sediment concentrations. Through these experimental data, the study seeks not only to gain a deeper quantitative understanding of how these two key variables influence sediment discharge efficiency but also to derive a universal sediment discharge curve capable of effectively predicting discharge trends at different Orifice elevations. The findings of this research will provide reservoir managers with more scientific and precise sediment discharge strategies, thereby extending reservoir lifespan and optimizing water resource management efficiency. Furthermore, this study will offer a valuable foundation for future reservoir management systems to achieve sustainable water resource utilization and effective sediment discharge.

1.2 Literature Review

1.2.1 Settling Time

i. Settling curves under different concentrations can be unified through dimensionless analysis. Lateral scale has little effect, while vertical scale only influences the duration of the constant settling phase; the overall mechanism remains unchanged (Hsu and Yu, 2007).

ii. In cohesive sediments, flocculation reduces settling velocity and causes "hindered settling," forming a clear water–mud interface with stable stratification (Hsu, 2012).

iii. The timing of the sharp concentration drop depends on interface velocity and orifice height, occurring earliest at high orifices and latest at bottom orifices, which sustain high-concentration discharge longer (Xu and Cao, 2024; this study).

1.2.2 Sediment Discharge Efficiency

i. Bottom orifices (ratio ≈ 0.10) maintain efficiency above 0.70 even in later stages, while high-level orifices (ratio ≈ 0.25) show only about 0.35 and decline nearly linearly with height (Jenzer Althaus et al., 2015).

ii. A single flush through a bottom gate removes about 1.8 times more sediment than higher orifices. Orifices below 0.25 of the water depth are recommended to delay efficiency loss and extend the high-efficiency period (Castillo et al., 2015).

iii. Bottom orifices connect directly to the dense turbidity current, preventing premature withdrawal of clear water and showing greater discharge stability than higher orifices (Morris and Fan, 2009).

1.2.3 Sediment Concentration

i. At low initial concentrations, interface formation is weak and concentration data less reliable (Hsu and Yu, 2007).

ii. Depth profiles show a gradient decrease, matching the pattern where bottom orifices sustain high concentration while high-level orifices drop rapidly (Julien, 2010; this study).

iii. Long-term models confirm that high-level orifices lose effectiveness as sedimentation progresses, whereas bottom orifices continue to discharge efficiently, consistent with engineering observations (Huang et al., 2015).

1.2.4 Orifice Height

i. Sediment discharge efficiency is strongly governed by orifice elevation. When the orifice lies below the clear water–mud interface, discharge concentration follows a linear distribution (Fan, 2008).

ii. Low-level orifices decay more slowly over time, making orifice height a critical geometric factor (Jenzer Althaus et al., 2014). Placing orifices below 0.25 of water depth intercepts the dense mud layer and sustains high efficiency (Castillo et al., 2015).

iii. At bottom orifices, the interface arrives about 20% later than at high-level orifices, keeping concentration 1.5–2 times higher during this period (Xu and Cao, 2024).

iv. Such configurations also prevent premature withdrawal of low-concentration water, ensuring efficiency and reservoir capacity, thus making bottom orifices the optimal placement (Morris and Fan, 2009).

1.2 Research Flowchart

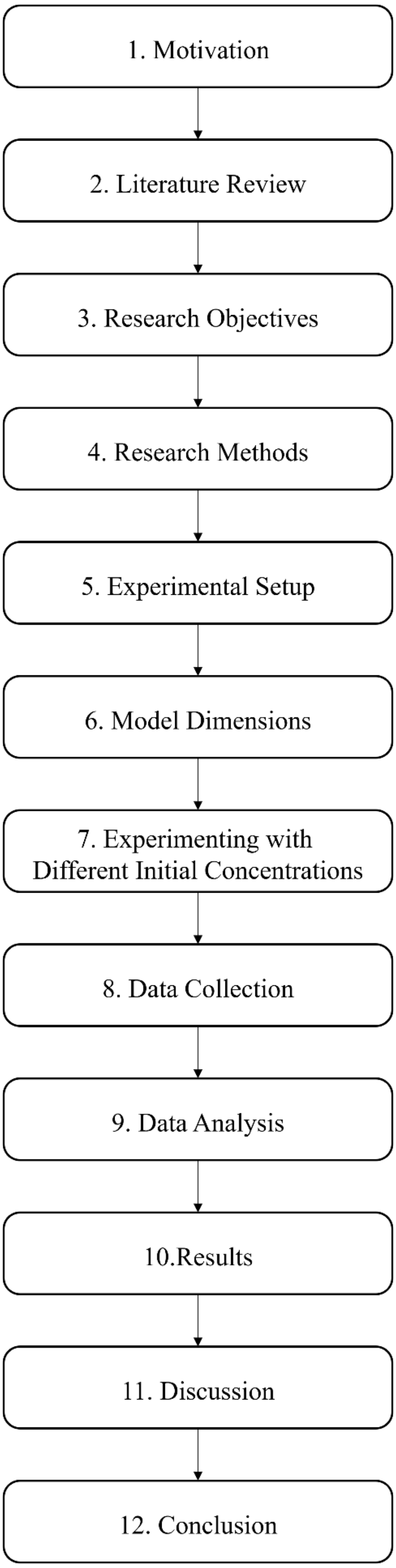

Fig. 1.1 Research Flowchart

Chapter 2 Research Methods

2.1 Experimental Setup

The experiment used a transparent acrylic settling column, 50 cm tall, with five vertically aligned orifices at different heights and a constant water level fixed at 45 cm. This setup simulates reservoir conditions and allows direct comparison of desilting performance at different outlet elevations . The settling column is shown in Figure 2.1 and Figure 2.2

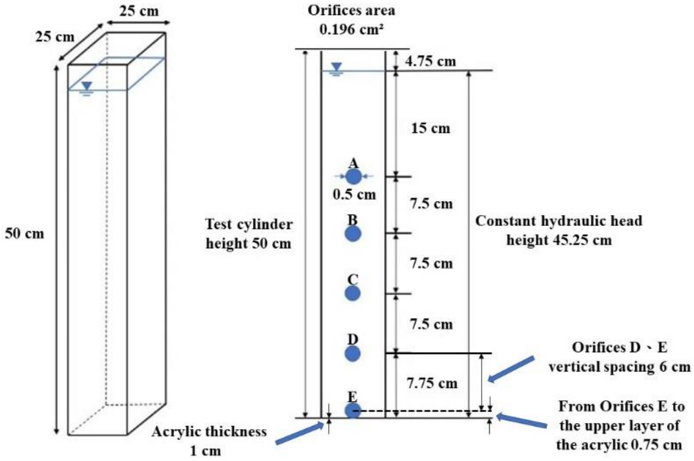

Fig. 2.1 Experimental settling column and dimensions.

Fig. 2.2 Experimental settling column

2.2 Number of experimental groups

This study used a settling column to control experimental conditions. Three initial sediment concentrations (40,000, 50,000, and 60,000 ppm) were tested at five outlet heights under a constant water level of 45 cm. The experimental combinations are summarized in Table 2.1

Table 2.1 The combinations of the number of experimental groups

Experiment Objectives	Initial concentration (ppm)	Orifice position	Water level (cm)
Exploring the effects of sand concentration and Orifice height on the concentration of the effluent sample.	40000ppm	Orifice A~E	Fixed water level 45 cm
	50000ppm		
	60000ppm		

2.3 Extract the sand weight from the sample.

Each sample was collected in a container, oven-dried for 24 hours, and then weighed. The net sand mass was obtained by subtracting the container weight, providing the sediment concentration at different times.

2.4 Calculate the kaolin concentration in the sample

$$\boldsymbol{Mass\ ratio = \frac{mass\ of\ solute\ (sand)}{mass\ of\ solution}} \quad \textbf{(6)} \qquad \boldsymbol{Mass\ ratio = \frac{W\_dry\_sand}{W\_solution}} \quad \textbf{(7)}$$

2.5 Calculate sand discharge efficiency

$$\textbf{Sediment Release Efficiency (\%)} = \frac{\sum \boldsymbol{Total\ Outflow\ Sediment}}{\sum \textbf{Total Inflow Sediment}} \quad \textbf{(8)}$$

2.6 Dimensionless Equation

To compare results under different conditions, the concentration data were converted into dimensionless form. Each concentration was normalized by its initial value ($C(t)/C_0$), and time was scaled by the total experiment duration (t/t_{total}). This transformation allows the discharge trends from different cases to be compared on a unified basis.

$$\boldsymbol{C^* = \frac{C(t)}{C_0}} \quad \textbf{(9)} \qquad \boldsymbol{t^* = \frac{t}{t_{total}}} \quad \textbf{(10)}$$

Chapter 3 Research Results

3.1 Concentration Profiles at Various Orifice Heights

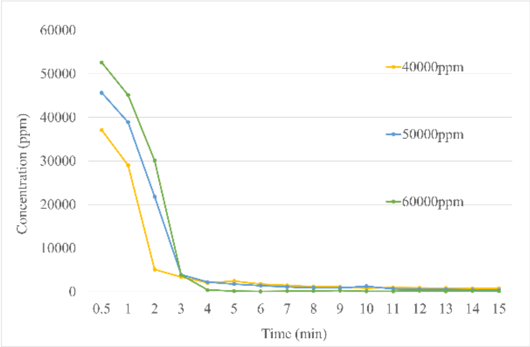

Fig. 3.1 Orifice A.

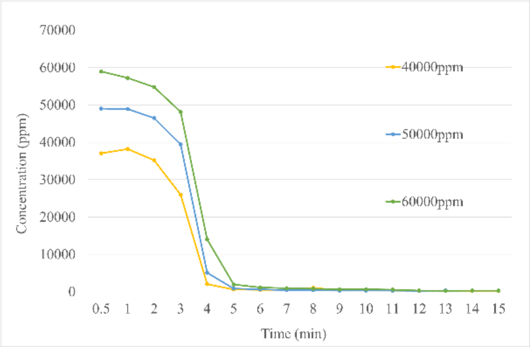

Fig. 3.2 Orifice B.

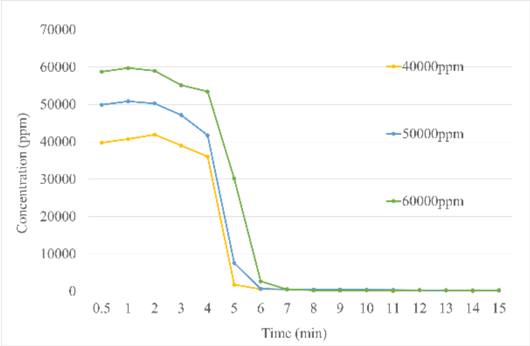

Fig. 3.3 Orifice C.

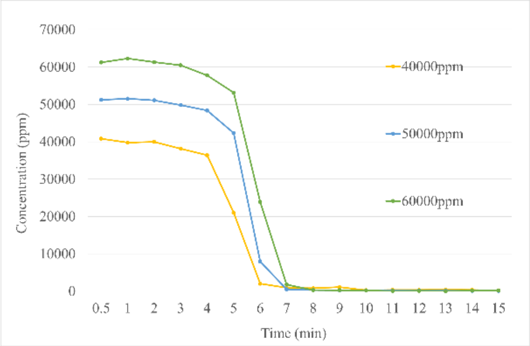

Fig. 3.4 Orifice D.

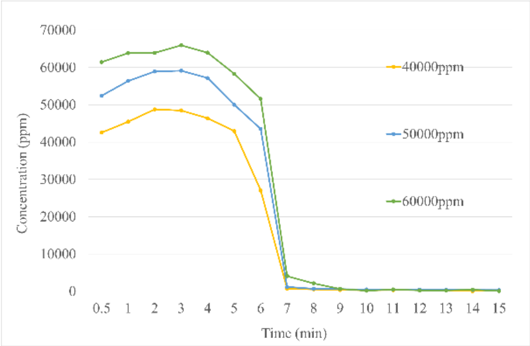

Fig. 3.5 Orifice E.

3.2 Sediment Discharge Efficiency of Different Orifice Configurations

Table 3.1 Sand Discharge Efficiency Statistics (Percentage)

orifice	40000ppm	50000ppm	60000ppm
A	10.87%	17.11%	17.28%
B	30.15%	28.43%	31.90%
C	40.32%	45.62%	49.16%
D	58.92%	63.10%	67.21%
E	86.79%	86.41%	89.45%

The research clearly confirms a significant correlation between desilting efficiency and the height of the sluice Orifice. The efficiency shows a near-linear increasing trend as the Orifice position is lowered. The bottommost Orifice, E, achieved a desilting efficiency exceeding 86%, far superior to the topmost Orifice, A. shown in Figure 3.6

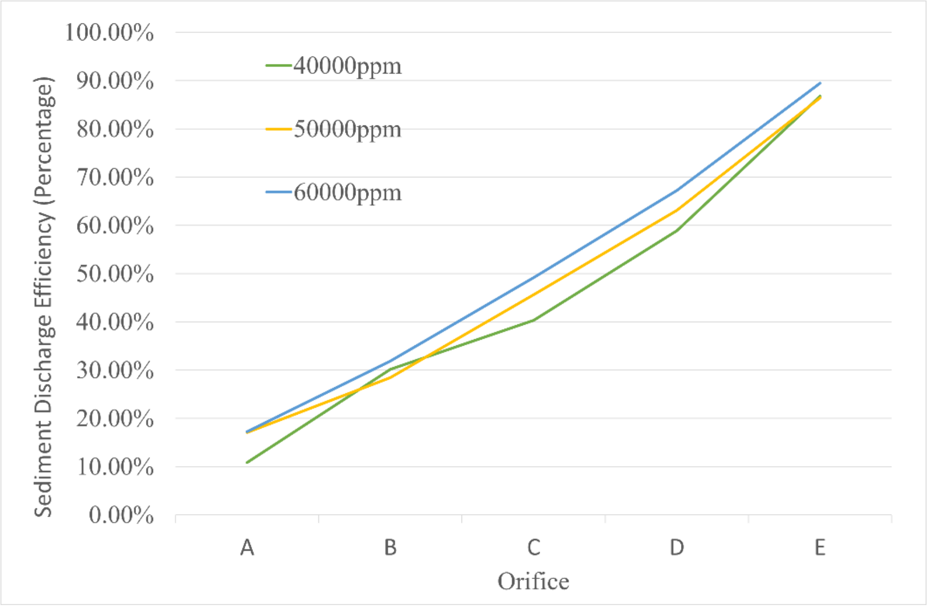

Fig. 3.6 Superimposed Plot of Sediment Discharge Efficiency Curves

Chapter 4 Discussion

4.1 Dimensionless Trend Analysis

After dimensionless transformation, concentration curves from different initial conditions collapse into a single trend. The sharp concentration drop consistently occurs at the same dimensionless time, indicating that discharge behavior depends mainly on orifice height rather than initial concentration. This provides the basis for developing a universal sediment discharge model. As shown in **Fig. 4.1~4.5**

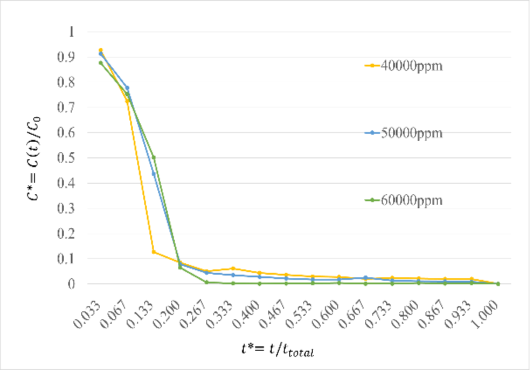

Fig. 4.1 Orifice A

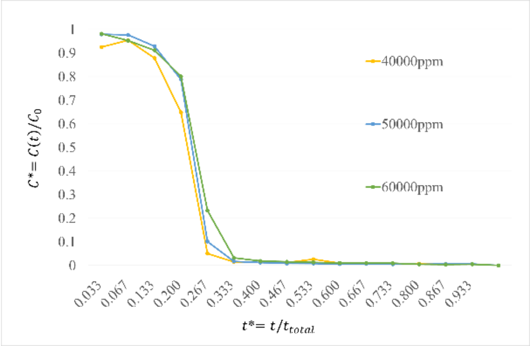

Fig. 4.2 Orifice B

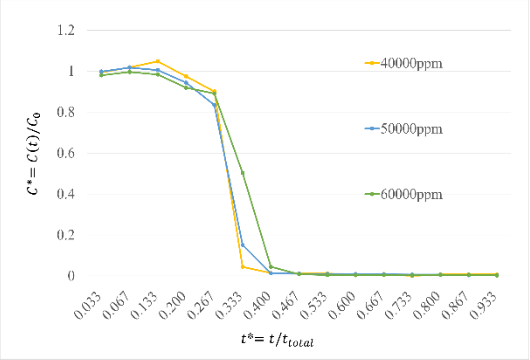

Fig. 4.3 Orifice C

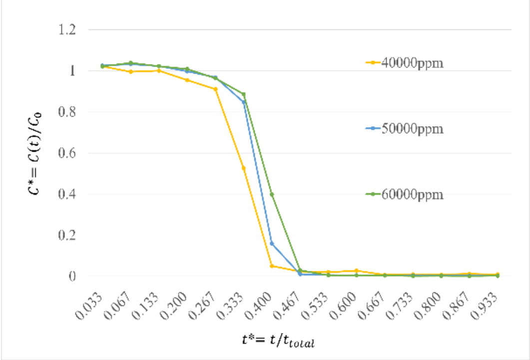

Fig. 4.4 Orifice D

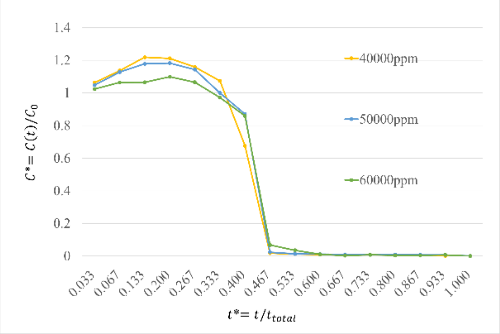

Fig. 4.5 Orifice E

4.2 Analysis of Sand Discharge Efficiency Changes at Different Orifice Heights

This experiment simulates reservoir desilting by investigating the sediment discharge efficiency at five vertically arranged orifices. The experiment was conducted under a constant head; therefore, pressure does not affect how the efficiency for any given orifice varies with time. For experiments with various initial concentrations (ranging from 40,000 ppm to 60,000 ppm), the resulting ranges of sediment discharge efficiency for each orifice are as follows:

Table 2.2 sand discharge efficiency ranges (Percentage)

Orifice Position	sand discharge efficiency ranges
A	10% to 17%
B	28% to 31%
C	40% to 49%
D	58% to 67%
E	86% to 89%

The data indicates that the sediment discharge efficiency of the uppermost orifice, Orifice A, is not ideal. This is primarily due to its high elevation, coupled with the rapid settling speed of the Kaolin particles, which leads to the quick clarification of the upper water layer and limits the amount of sediment available for discharge . In contrast, the bottom-most orifice, Orifice E, exhibits the most significant discharge efficiency, capable of discharging over 86% of the initial sediment mass within the acrylic column. The experimental results show that from Orifice A to Orifice E, the sediment discharge efficiency exhibits a near-linear increasing trend across all initial concentrations.In summary, moving from top to bottom, the lower the orifice elevation (i.e., further from the water surface and closer to the column base), the better its sediment discharge efficiency, demonstrating that the bottom-most orifice, Orifice E, is the most effective for desilting. In agreement with published literature and field observations.

Chapter 5 Conclusions

This study verifies the influence of orifice height and initial sediment concentration on desilting efficiency through systematic model tests. The main conclusions are as follows:

5.1 Orifice Height as a Key Factor in Desilting Efficiency:

The results confirm a strong correlation between desilting efficiency and orifice height. Efficiency increases almost linearly as the orifice is lowered. The bottommost orifice (E) reached over 86% efficiency, far higher than the topmost orifice (A). This agrees with existing literature and engineering observations, showing the clear advantage of low-level orifices in removing concentrated bottom sediment.

5.2 Universal Desilting Curve Model:

A major contribution of this research is consolidating temporal concentration data into a single universal curve through dimensionless analysis. Within the 40,000–60,000 ppm range, the desilting trend is consistent and unaffected by initial concentration.

5.3 Mechanism of the "Concentration Plunge Point":

The sharp concentration drop occurs later when the orifice is positioned lower. This happens when the turbid–clear interface falls below the orifice, after which only low-concentration water is discharged. Lower orifices delay this point, maintaining high-concentration discharge longer and explaining their higher efficiency.

In conclusion, this study clarifies how orifice height controls desilting efficiency and establishes a predictive universal model. The model provides a scientific basis for optimizing reservoir operations, achieving maximum sediment removal with minimal water use, and supporting sustainable reservoir management.

Chapter 6 References

i. Castillo, L. G., Carrillo, J. M., and Álvarez, M. A., "Complementary Methods for Determining the Sedimentation and Flushing in a Reservoir," Journal of Hydraulic Engineering, 2015.

ii. Fan, J., "Stratified flow through outlets," Journal of Hydro-environment Research, Vol. 2, No. 1, pp. 3-18, 2008.

iii. Jenzer Althaus, J. M. I., De Cesare, G., and Schleiss, A. J., "Sediment Evacuation from Reservoirs through Intakes by Jet-Induced Flow," Journal of Hydraulic Engineering, 2014.

iv. Morris, Gregory L., and Fan, Jiahua., Reservoir Sedimentation Handbook, McGraw-Hill Book Co., New York, 1998.

v. Xu, Huan, and Cao, Zhixian., "Experimental study of reservoir flushing through a bottom tunnel initially covered by cohesive sediment," International Journal of Sediment Research, Vol. 39, pp. 327-339, 2024.

vi. 許少華、俞維昇，「實驗尺度對黏性泥砂界面沉降之影響—石門水庫淤泥沉澱試驗」，臺灣水利，第 55 卷，第 4 期，pp. 13-20，2007。

vii. 黃振家、李豐佐、古涵山、廖翊鈞、賴進松、欉順忠、譚義績，「水庫淤積演變之長期趨勢推估」，2015。